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Comments on "A Three-Dimensional Model of Dynamical Processes in the Venus Atmosphere"

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29 May 1979 and 17 July 1979

1. Introduction

Young and Pollack (1977; also see Pollack and Young, 1975) present the results of a major attempt to simulate numerically the three-dimensional circulation of the atmosphere of Venus. Their attempt is the first that has had any success at reproducing observed features of the upper atmosphere such as the 4-day circulation and the Y-pattern found in ultraviolet photographs. Consequently, they concluded that they had found "solutions to the governing equations of motion which are representative of the dynamical regimes occurring in the Venus atmosphere" (p. 1348, Young and Pollack, 1977). However, we believe that there are substantial questions regarding the validity of their model and the proper interpretation of their results which they do not adequately discuss. These questions are so substantial that we doubt, in fact, that they have found valid solutions representative of the Venus atmosphere. We will not consider here whether the external forcing, boundary conditons and parameter values assumed in Young and Pollack's calculations are representative of Venus' atmosphere; rather we will address only the question of whether the physics which is responsible for their results has been formulated correctly.

In Young and Pollack's model, the global mean temperature structure is specified and constant. Thus, only the horizontal temperature structure at each altitude can respond to the differential solar heating and dynamics. In equilibrium a balance between the parameterized horizontal heat diffusion and differential solar heating controls the mean meridional temperature structure, so that the model dynamics does not have much influence on the equator-to-pole temperature gradient (p. 1342). Con-sequently, a major part of the interaction between the dynamics and the temperature structure is missing from this model; therefore, the momentum balance in the model results is of greater interest.

In Young and Pollack's equilibrium solutions, the balancing terms in the momentum conservation equations, *which determine the equilibrium mean zonal wind*, are the parameterized *vertical* momentum diffusion, the mean meridional advection and horizontal eddy transport terms (p. 1335). Consequently, the formulation of these three terms must be physically realistic if their results are to be meaningful. In the following two sections, we consider the formulation of the vertical momentum diffusion and large-scale dynamics, respectively.

2. Formulation of vertical momentum diffusion

Young and Pollack's formulation of the vertical momentum diffusion introduces two spurious forces. Consider the vertically integrated time rate of change of their zonal momentum equation, obtained by multiplying the u_ϕ component of the equation of motion by the density ρ and integrating by parts over height z. If we ignore the horizontal diffusion, rotation and pressure gradient terms for clarity, their equation becomes

$$\int_0^{Top} \rho \frac{Du_\phi}{Dt} dz = - \int_0^{Top} \rho\nu_{0v} \frac{\partial^4 u_\phi}{\partial z^4} dz$$

$$= - \left[\rho\nu_{0v} \frac{\partial^3 u_\phi}{\partial z^3} \right]_0^{Top}$$

$$+ \nu_{0v} \int_0^{Top} \frac{\partial\rho}{\partial z} \frac{\partial^3 u_\phi}{\partial z^3} dz, \quad (1)$$

where ν_{0v} is a constant. The first spurious force is a stress at the top boundary caused by the fact that the boundary term in (1) is not zero there. The proper boundary condition at the top is that there should be no stress there, i.e.,

$$\frac{\partial^3 u_\phi}{\partial z^3} = \frac{\partial^3}{\partial z^3}\left[\frac{1}{\rho}\sum_{L,M}\left(\frac{1}{a\sin\theta}\frac{\partial S_L^M}{\partial z}\right.\right.$$
$$\left.\left.\times \frac{\partial Y_L^M}{\partial\phi} - \frac{T_L^M}{a}\frac{\partial Y_L^M}{\partial\theta}\right)\right] = 0, \quad (2)$$

but the top boundary conditions used by Young and Pollack [their eqs. (19) and (21)] do not insure the condition (2) as direct substitution demonstrates. Although this spurious boundary force cannot, *by itself*, produce mean zonal momentum because the zonal average of (2) is zero, *the spurious meridional motions that arise must affect the mean meridional advection term*, and, therefore, the equilibrium momentum balance in their model.

The second spurious force is a body force produced by the last term in (1), which results solely from the neglect of vertical density gradients in Young and Pollack's formulation of the vertical momentum diffusion. That this formulation can drastically affect the *equilibrium* zonal wind can be illustrated by a simple example. Consider the horizontal average of the zonal momentum equation in flux form, *viz.*,

$$\frac{\partial}{\partial t}(\overline{\rho u_\phi}) = -\frac{\partial}{\partial z}(\overline{\rho w u_\phi}) - F_{\mathrm{diff}}, \quad (3)$$

where the overbar indicates the horizontal average. The boundary conditions on the vertical velocity w make the vertical integral of the first term on the right equal to zero; i.e., the large-scale motions conserve momentum while diffusion does not, solely because of the no-slip boundary condition at the surface. As a convenient test case, we replace the advection term by a simple delta-function forcing near the top and bottom of an atmosphere of depth $D > H$, the atmospheric scale height, i.e.,

$$\frac{\partial}{\partial z}(\overline{\rho w u_\phi}) = F_0[\delta(z - D^*) - \delta(z - d^*)], \quad (4)$$

where $D - D^* \ll 1$ and $d^* \ll 1$. This forcing drives oppositely directed winds near the top and bottom of the model atmosphere and satisfies the conservation condition.

We can now solve (3) analytically for the equilibrium zonal velocity at the top of the atmosphere by setting the left side to zero and substituting for F_{diff} either the correct diffusion

$$F_{\mathrm{diff}} = \frac{\partial}{\partial z}\left(\rho\nu_{0v}\frac{\partial^3 u_\phi}{\partial z^3}\right) \quad (5)$$

or the Young and Pollack form

$$F_{\mathrm{diff}} = \rho\nu_{0v}\frac{\partial^4 u_\phi}{\partial z^4}, \quad (6)$$

where the horizontal average is understood. We also use $\rho = \rho_0\exp(-z/H)$ with constant H for convenience. With the boundary conditions $u = 0$ at $z = 0$ and $\partial u/\partial z = \partial^3 u/\partial z^3 = 0$ at $z = D$ and the correct diffusion, we integrate (3) to get

$$u_c(D) = \frac{F_0}{\rho_0\nu_{0v}}H^2\left(-De^{D/H} + He^{D/H} - H + \frac{1}{2}\frac{D^2}{H}\right)$$

or for $D \gg H$,

$$u_c(D) \approx -\frac{F_0}{\rho_0\nu_{0v}}H^2De^{D/H}. \quad (7)$$

With Young and Pollack's diffusion, we get

$$u_{yp}(D) = -\frac{F_0}{\rho_0\nu_{0v}}H^2De^{D/H}\left[\frac{1}{3}\left(\frac{D}{H}\right)^2\right]. \quad (8)$$

Note that in the absence of any forcing, $F_0 = 0$, both forms of diffusion give the correct answer that $u(D) = 0$ in equilibrium, a result found by Young and Pollack when they removed all of the nonlinear terms from their momentum equations (p. 1337). However, this calculation demonstrates the important result that *the interaction between the incorrect diffusion and the forcing terms can change the equilibrium zonal wind by large factors*. For example, when $D \approx 4H$ as is implied by Young and Pollack's Fig. 1, $u_{yp}(D)$ is more than five times larger than the correct value, $u_c(D)$.

3. Truncation effects

Truncation of a spectral model at small wavenumbers produces many distortions of the simulated dynamics, not all of which are confined to high wavenumbers, even when the energy in these high wavenumbers is very small (see, e.g., Puri and Bourke, 1974). The truncation at total wavenumber 4 used by Young and Pollack limits to 24 the number of spherical harmonic modes[1] retained in their representation of the prognostic variables, but they assume that the flow is symmetric about the equator which further restricts the number of harmonic modes to only 10. (These modes include four wave pairs, each pair composed of modes with identical spatial structure but opposite phase speeds.) This truncation is so severe that we cannot accept their claim that this "resolution was adequate for resolving the essential dynamical processes" (p. 1320).

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[1] We are referring to the number of modes in a spherical harmonic expansion of the vorticity equation (cf., Baines, 1976) which is equivalent to Young and Pollack's formulation.

For example, one dynamical process which is not properly simulated with this severe truncation is the shear (or barotropic) instability of the only other zonal flow mode besides solid rotation retained with this truncation, the one with two nodes in the meridional direction in each hemisphere. This mode is clearly present in Young and Pollack's solution I (see their Fig. 2). Baines (1976) specifically shows that this zonal flow mode is most unstable to a pair of waves with zonal wavenumbers 2 and 4 which are antisymmetric about the equator, waves which have been excluded from Young and Pollack's model. In fact, we conclude from Baines' results that Young and Pollack's model retains too few modes to simulate properly the shear instability of any of the seven potentially unstable modes that are retained in their model; hence these modes are artificially stabilized. Since Baines' inviscid calculations retain only a few modes to simplify the interactions, we must turn to higher resolution calculations to examine the complete evolution of shear unstable flows. Such calculations show that, in the absence of forcing, the amplitude of shear unstable modes can be drastically altered by the instability (Rossow and Williams, 1979). Whether or not shear instability plays an important role in Venus' atmosphere, the fact that *this model cannot properly simulate this process* makes it difficult to accept the claim that this model correctly simulates any of the essential nonlinear interactions, even for the resolved modes.

We also question the significance of finding a flow dominated by solid rotation and an oscillating Y-like pattern in their solution II. Since seven of the ten retained modes have harmonic indices 3 and 4 for which the diffusion times are less than 100 days, only three modes in their model are not strongly damped. These three modes must therefore contain the largest fraction of the total kinetic energy in the flow. *These three modes are just solid body rotation and the two zonal wavenumber 1 waves of op-posite phase speed which dominate the Y-like features in Young and Pollack's solution.*

4. Summary

The validity of any conclusions, drawn from Young and Pollack's model results, regarding mechanisms producing large zonal flows depends on the fidelity of the model physics to the physics of large-scale atmospheric motions. Except for stresses at the planetary surface, all model physics should conserve angular momentum, but Young and Pollack's vertical momentum diffusion formulation does not. Since vertical diffusion is fundamental to the momentum balance in the model's equilibrium state (pp. 1335, 1337), the two spurious diffusive forces may be important in determining the equilibrium zonal wind. Furthermore, the severe truncation and assumed symmetry, which eliminate most of the wave modes, and the strong damping of all but three of the remaining modes may effectively inhibit the nonlinear interactions of the resolved modes. We believe that these problems with the dominant terms in the momentum equations raise serious doubts about the validity of Young and Pollack's conclusions.

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